

A Population Explosion: The Nature and Evolution of X-ray Binaries in Diverse Environments  
 28 Oct.–2 Nov. 2007, St. Petersburg Beach, FL  
 R.M. Bandyopadhyay, S. Wachter, D. Gelino, & C. R. Gelino, eds.  
 Session: *Jets*

## Searching for the signatures of jet-ISM interactions in X-ray binaries

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**Abstract.** Jets from X-ray binaries are continuously injecting matter and energy into the surrounding interstellar medium. However, there exist to date relatively few cases where jet-ISM interactions have been directly observed. We review the current examples, and go on to present new data on the proposed hotspots of GRS 1915+105, finding no concrete evidence for any association between the hotspots and the central source, in agreement with previous findings in the literature. We also present preliminary results on radio and H $\alpha$  searches for jet-ISM interactions around known X-ray binaries, and discuss strategies for future searches.

## 1. Introduction

The jets in X-ray binary systems have been estimated to inject  $\sim 1\%$  of the time-averaged luminosity of supernovae into the surrounding interstellar medium (ISM) (Fender et al. 2005). Heinz (these proceedings) has estimated that the jets also inflate lobes at a rate of  $\sim 5 \times 10^{48} \text{ cm}^3 \text{ s}^{-1}$ , comparable to a significant fraction of the volume of the Galactic disc over the lifetime of the Galaxy. Furthermore, the  $\mu\text{G}$ -level magnetic fields they inject into their surroundings could be responsible for seeding the Galactic magnetic field. However, despite the undisputed importance of the effects of X-ray binary jets on their environments,

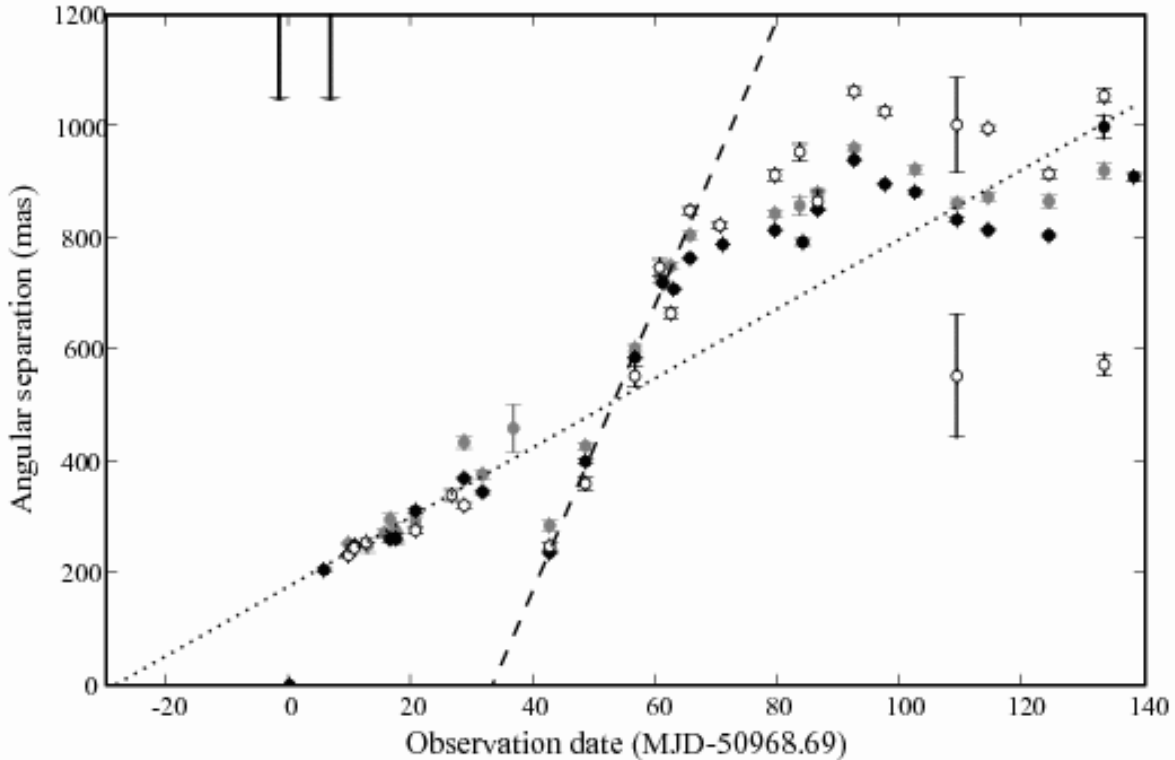


Figure 1. Measured angular separation from the core of the radio knots in the 1998 outburst of XTE J1748-288. Radio observations were made at 5, 8.4 and 15 GHz, and day 0 is the ejection date inferred from X-ray observations. Open symbols are for 15 GHz, filled black symbols for 8.4 GHz, and filled grey symbols are for 5 GHz. The two arrows indicate the start and peak of the X-ray outburst (Brocksopp et al. 2007).

there are as yet relatively few cases where the interaction between the jets and the surrounding ISM has been directly observed.

Extended, stationary radio lobes have been observed around the two systems 1E 1740.7-2942 (Mirabel et al. 1992) and GRS 1758-258 (Martí et al. 2002). In three further cases, the large-scale nebulae inflated by the jets have been imaged in the radio band. The precessing jets of SS 433 are thought to have inflated the two ‘ears’ of the surrounding W 50 nebula (Begelman et al. 1980), a radio lobe aligned with the jets of Cyg X-1 was recently discovered by Gallo et al. (2005), and in Cir X-1, we observe the radio jets through the nebula which they have inflated (Tudose et al. 2006). Fomalont et al. (2001) monitored the radio lobes of Sco X-1 as they moved outwards, which were identified as the working surfaces where highly-relativistic beams impacted on the ambient medium. A similar case of a relativistic underlying flow lighting up downstream radio lobes has been observed in a second confirmed neutron-star system, Cir X-1 (Fender et al. 2004), and it has been suggested that a similar unseen shock is responsible for lighting up the X-ray jets in SS 433 (Migliari et al. 2005). Such impact sites have been directly detected in the X-ray band in the cases of XTE J1550-564 (Corbel et al. 2002) and H 1743-322 (Corbel et al. 2005), at angular separations of several arcseconds from the respective central binary systems. Actual deceleration of the jets as they sweep up the surrounding ISM has only been unambiguously observed in XTE J1550-564 (Kaaret et al. 2003), although evidence for deceleration has also been seen in the radio band in the system XTE J1748-288.

Figure 1 shows the measured angular separations of the radio knots from the core, as a function of time since the start of the corresponding X-ray flare during the 1998 outburst of XTE J1748-288. There must have been deceleration within 200 mas, before the first radio observations were made, since the fitted radio proper motion of  $6.2 \text{ mas d}^{-1}$  does not give a zero-separation date consistent with the X-ray flare. The proper motion then increases to  $25.5 \text{ mas d}^{-1}$  for  $\sim 20 \text{ d}$  before the jets seem to stall once more at an angular separation of  $\sim 1 \text{ arcsec}$ . This is a clear indication of complex interactions with the environment, and further analysis is warranted. Higher-frequency observations suggest multiple ejection events, which could help to explain the observed speeds, although the system is located in the direction of the Galactic Centre, so if it is not a foreground source, the surrounding environment is likely to be both dense and highly inhomogeneous, which could also explain the variable proper motions.

## 2. The proposed hotspots of GRS 1915+105

GRS 1915+105 is the prototypical microquasar, and has been in a continuous state of outburst since 1992. During its so-called plateau state, it exhibits a flat-spectrum conical jet with luminosity  $\sim 10^{38} \text{ erg s}^{-1}$ , but it periodically undergoes outbursts when relativistically-moving ejecta are observed and the jet power rises to  $\sim 10^{41} \text{ erg s}^{-1}$  (Fender & Belloni 2004). Despite being one of the most powerful relativistic jets known, no unequivocal evidence for interactions with the ISM has been seen in this system, possibly owing to its location in a relatively underdense region (Heinz 2002). A discrepancy in the proper motions of the jets measured on different angular scales (Mirabel & Rodríguez 1994; Fender et al. 1999) was initially suggestive of deceleration within a few hundred milliarcseconds of the central binary, but Miller-Jones et al. (2007), collating all available data on the relativistic outbursts of the source, found no conclusive evidence for deceleration.

Rodríguez & Mirabel (1998) examined the surroundings of GRS 1915+105, and tentatively identified two possible hotspots well-aligned with the arcsecond-scale jets and equidistant from the source at an angular separation of 17 arcmin. Chaty et al. (2001) observed these sources in the radio, millimeter and infrared bands and found no clear evidence that they were associated with GRS 1915+105. More recently, Kaiser et al. (2004) presented a self-consistent model of these two sources as hotspots, identifying the non-thermal filament pointing back from the southwestern hotspot to the central binary as emission from the end of the jet where it impinged on the ambient medium. Taking the perspective that absence of evidence is not in itself evidence of absence, we made further follow-up observations of the south-western hotspot, IRAS 19132+1035, to test this hypothesis using the VLA and MERLIN arrays and the *Chandra* X-ray telescope.

VLA 1.4 GHz observations showed that the flux density of the proposed hotspot had not changed between 1997 and 2005, despite at least 9 flaring sequences occurring in the central source during this time. However, given the propagation time of  $\geq 25 \text{ y}$  for jet material to travel down the jet to the candidate hotspot, then since the source only switched on in 1992, we might not necessarily expect to see any variability of the hotspot region. Alternatively, the observed variability of the central source could be smoothed out during its propagation down the jet. To explore the nature of the non-thermal filament, and determine whether it could simply be a background AGN coincidentally located close to the hotspot and oriented along the position angle of the arcsecond-scale jets of GRS 1915+105, we made high-resolution radio observations with MERLIN. Only 20% of the 1.4-GHz radio flux density seen with the VLA was recovered, suggesting that the majority of the emission from the non-thermal filament was from a more diffuse, large-scale structure which was being spatially filtered

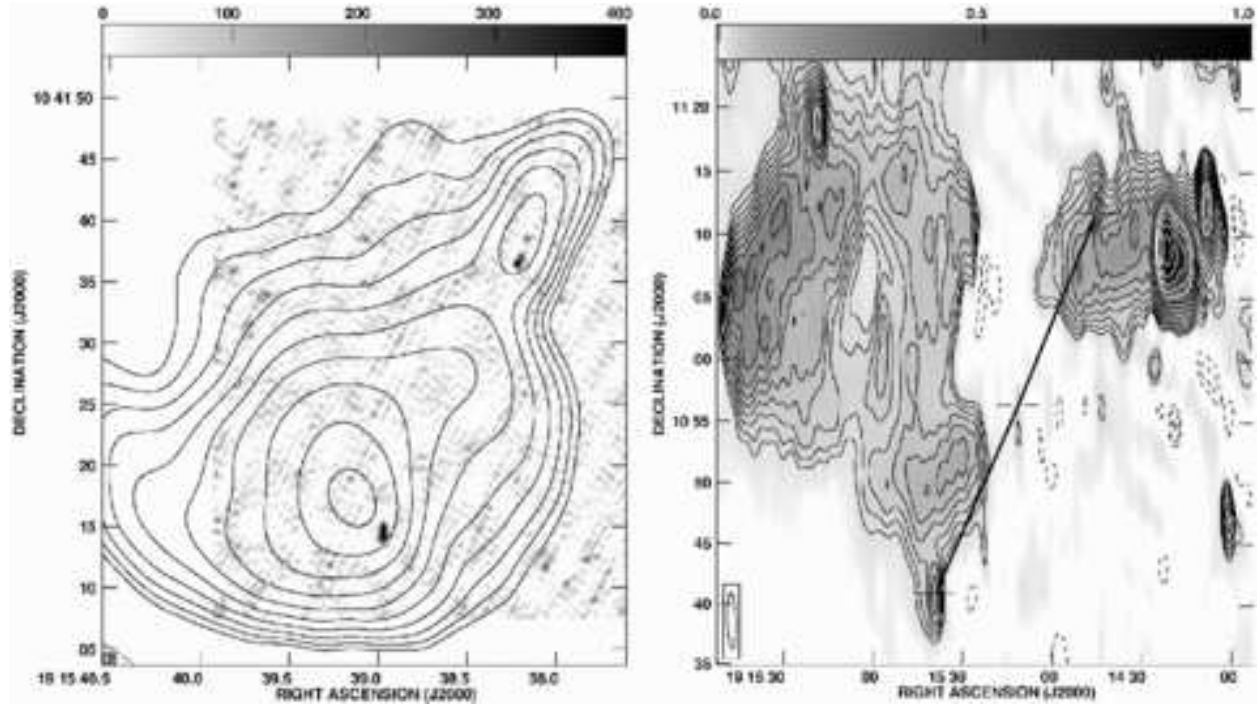


Figure 2. *Left:* Overlay of the VLA 1.4-GHz contours on the MERLIN greyscale image of the southeastern hotspot candidate source IRAS 19132+1035. Contours are at levels of  $\pm(\sqrt{2})^n$  times  $300 \mu\text{Jy bm}^{-1}$ , where  $n = 3, 4, 5, \dots$ , and the greyscale is in  $\mu\text{Jy bm}^{-1}$ . *Right:* WSRT 350-MHz image of the field surrounding GRS 1915+105, with crosses marking the positions of the central source and the candidate hotspots. The greyscale is in  $\text{Jy bm}^{-1}$  and the contours are at levels of  $\pm(\sqrt{2})^n$  times the rms of  $3.9 \text{ mJy bm}^{-1}$ , where  $n = 3, 4, 5, \dots$

out on the longer MERLIN baselines. This would appear to be inconsistent with an AGN interpretation. Also, the morphology of the observed emission does not resemble the typical core-hotspot structure of a background FR II radio galaxy (Fig. 2, left panel). No spatially-extended bowshock structure was observed from the southern border of the VLA source, although the jet model of Kaiser et al. (2004) makes no prediction as to the morphology of the hotspot region. The *Chandra* observations detected no significant emission at the position of the candidate hotspot ( $8 \pm 8$  counts; consistent with zero, but also at the  $3\sigma$  level with half the 60 counts expected from an extrapolation of the radio measurement, assuming a standard synchrotron spectrum), suggesting that if this is the interaction region, any shock acceleration is weaker than has been seen in sources such as XTE J1550-564, and is insufficient to power X-ray lobes. Thus even with the new data, we still cannot either fully confirm or deny an association between the candidate lobes and the central binary, just as found by Chaty et al. (2001). It should be noted that the HI distance to the two hotspot candidates is 6.5 kpc, significantly closer than the  $\sim 11$  kpc that is usually assumed for GRS 1915+105. Recent work by Dhawan et al. (2007) found that the peculiar motion of the central binary system is minimized for a source distance of 9 kpc, which would rule out any association with the candidate hotspots, although the authors do not exclude a closer distance should the system have received a substantial natal kick during the formation of the black hole.

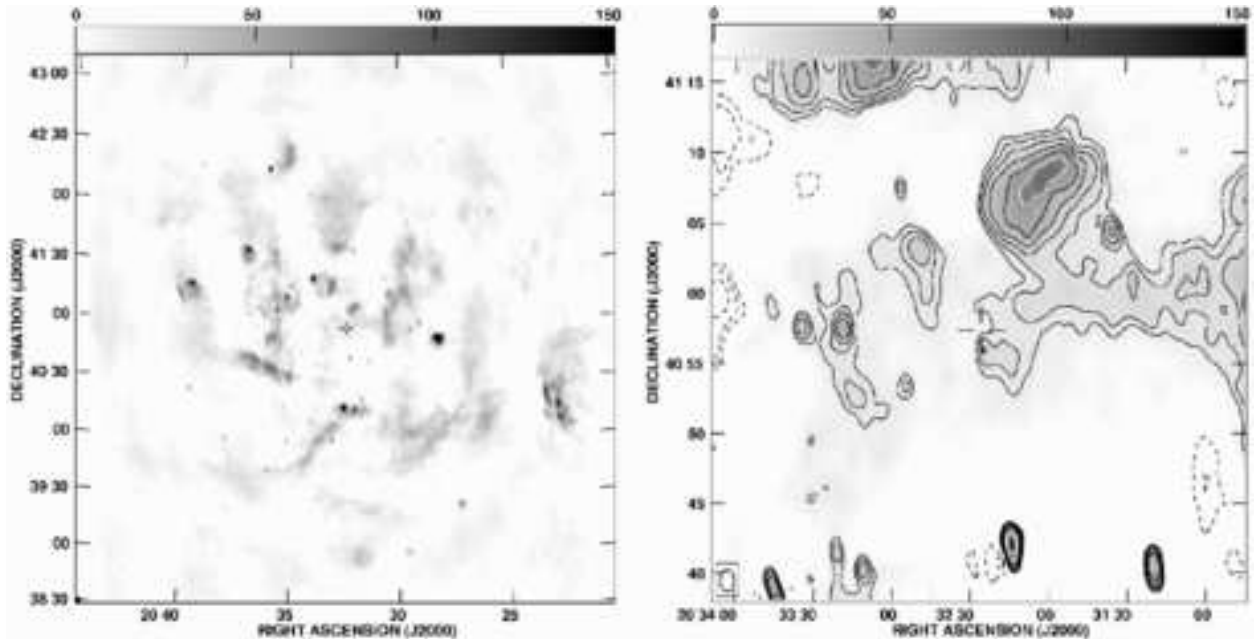


Figure 3. *Left:* WSRT-350-MHz image of the field surrounding Cygnus X-3. Greyscale is in  $\text{mJy bm}^{-1}$ . *Right:* Zoomed-in image of the region surrounding the binary system. The greyscale is in  $\text{mJy bm}^{-1}$  and the contours are at levels of  $\pm(\sqrt{2})^n$  times the rms of  $2.2 \text{ mJy bm}^{-1}$ , where  $n = 3, 4, 5, \dots$ . In both panels, the cross marks the location of the central binary system.

### 3. Searching for lobes with low-frequency radio observations

In order to look for evidence of jet-blown lobes surrounding three of the most powerful known X-ray binary systems, and to characterise their behaviour at low frequencies, we observed the fields surrounding GRS1915+105, Cyg X-3, and SS 433 with the WSRT at 350 and 140 MHz. The right-hand panel of Fig. 2 shows the field surrounding GRS1915+105. While the two hotspot candidates described in Section 2 were both detected, with spectra consistent with those found at higher frequencies by Chaty et al. (2001), there was no evidence for any extended emission linking them back to the central binary system. This is consistent with the findings of Kaiser et al. (2004), who predicted that the synchrotron luminosity of any such lobes ought to be of order  $0.08 \text{ mJy bm}^{-1}$  at 1.4 GHz, below the sensitivity of the current generation of radio telescopes.

In Cygnus X-3, there was also no evidence for any extended lobes. The line of sight passes through the Cygnus OB2 association, a dense field with significant extended emission and many point sources. Figure 3 shows the field surrounding the X-ray binary, with the full WSRT 350-MHz field of view on the left and a zoomed-in version on the right. It is clear that there is too much diffuse emission in the field to unambiguously associate any structures with the central binary system. The central binary was not detected at either frequency, and a comparison to 15-GHz monitoring data from the Ryle Telescope (Pooley; <http://www.mrao.cam.ac.uk/~guy/cx3/>) implies that there must be a turnover in the spectrum, either due to self-absorption or free-free absorption. The source was however significantly detected in later observations during its giant radio outburst of 2006 at a level of 2 Jy at 140 MHz.

#### 4. Searching for lobes with $H\alpha$ observations

The jet-blown lobe in Cyg X-1 was detected both in the radio band and in deep narrowband optical images taken in the  $H\alpha$  and  $[O\text{ III}]$  ( $5007\text{ \AA}$ ) filters (Russell et al. 2007). The luminosity and morphology of the latter emission is indicative of shock-excited gas with velocity  $v_{\text{shock}} > 100\text{ km s}^{-1}$ . A search for optical nebulae around X-ray binaries (Russell et al. 2006) identified three promising candidates around the sources GRO J1655-40, GRS 1009-45, and LS 5039. A cavity in  $H\alpha$  around GRO J1655-40 was observed, and a shell which aligned well with diffuse radio emission in the region. The lobe was also detected in  $[S\text{ II}]$  emission, a tracer of shock-excited gas, and low-frequency 843-MHz MOST emission appeared to trace the outline of the cavity well. Deeper VLA observations of GRO J1655-40 and LS 5039 have been taken in order to attempt to unambiguously determine whether the cavities are real, and whether they are in fact associated with their respective central binaries. In one further (extragalactic) case, the  $H\alpha$  nebula surrounding LMC X-1 is likely to be both photoionized by the X-ray source and shock-excited by its jets (Cooke et al. 2007).

#### 5. Observing strategies

Extensive observation campaigns have thus far failed to identify many examples of jet-ISM interactions or jet-blown lobes around X-ray binary systems. There is still no evidence for the effects of some of the most powerful known jets, such as those of GRS 1915+105, on their surroundings. Since the time-averaged power output of such transient jets is thought to be comparable to that of the compact, steady jets (Heinz & Grimm 2005), there is no reason to target only the brightest systems in a search for such interactions. As argued by Heinz (2002), since most X-ray binaries are located in dynamically underdense environments when compared to AGN, local density enhancements are required to slow the jets via interaction with the ISM. A further possibility is that in order to inflate jet-blown lobes, the central source must have a low peculiar velocity relative to the local standard of rest. Cyg X-1 has a velocity of only  $9 \pm 2\text{ km s}^{-1}$  relative to the nearby Cygnus OB 3 association (Mirabel & Rodrigues 2003), such that the effectively constant jet direction has allowed it to inflate the large-scale lobe over its 0.02–0.06 Myr lifetime (Russell et al. 2007). For other X-ray binaries which received higher natal kicks during their formation, the jet direction might not be sufficiently stable to inflate large-scale nebulae, although this would not rule out interaction with the ISM at the points of jet impact, as seen in XTE J1550-564 or Sco X-1.

In order to detect extended emission surrounding X-ray binaries in the radio band, it is necessary to observe at low frequencies in compact configurations to probe the diffuse emission from the jet-blown nebulae. Synchrotron emission will be brightest at lower frequencies, and deep integrations are needed to pick out low surface brightness emission. Detecting polarized emission from such lobes could help to prove that the emission was of synchrotron origin from the high-energy electrons in the jets, filtering out unwanted thermal emission from the complex Galactic fields in which many X-ray binaries are located. Instruments such as LOFAR and the MWA, with their wide fields of view, could help in detecting more candidate objects. However, extended radio emission alone cannot necessarily prove an association between any candidate nebulae and their central objects, and a multiwavelength approach, such as combining radio with narrowband optical observations, is often required to definitively identify jet-inflated lobes.

## 6. Conclusions

X-ray binary jets are continuously injecting energy, momentum and magnetic fields into their surroundings, and the signs of these interactions can be directly observed in some cases. However, detection of such interactions requires fairly special conditions, in particular low peculiar velocities and local density enhancements in the environments of the sources. A second, in-depth, multiwavelength study has revealed no firm evidence for jet-blown lobes around GRS 1915+105, and a secure distance determination (e.g. via trigonometric parallax) appears to be the only way to conclusively confirm or rule out an association with the two IRAS sources identified by Rodríguez & Mirabel (1998).

**Acknowledgments.** Support for this work has been provided in part by NASA through Chandra Award SAO G06-7026X-R. JM-J is a Jansky Fellow of the NRAO. The NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc.

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